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Skyrmion spin structure of exchange-coupled magnetic core-shell nanodisk

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We study the skyrmion spin texture created in a cylindrical exchange-coupled magnetic core-shell nanodisk (Co/CoPt) in absence of the Dzyaloshinskii-Moriya interaction. The evolution of the skyrmion spin texture under varying applied field is investigated. The skyrmion core size can be tuned by an external magnetic field. However, skyrmion spin texture will be destroyed for a large enough applied field. With the stability and controllability of magnetic states, the exchange-coupled magnetic core-shell nanodisk can make a high potential for future storage media and devices, with the storage of data in the form of skyrmions.

Keywords: micromagnetics, skyrmions, core-shell nanostructure

I. INTRODUCTION

Fig. 1 HERE

The intriguing spin configurations – magnetic skyrmions [1, 2], which hold promise as information carriers in ultra-dense memory and logic devices [3-5], are always associated with the chiral magnetic interaction, namely Dzyaloshinskii-Moriya interaction (DMI). However, several novel works present new approaches to create skyrmion spin texture in nanostructures in the absence of DMI [6-11]. On the other hand, the core-shell nanomagnets are expected to be applied in patterned recording with higher density recently, where each core-shell unit could record more than two states [12]. In this paper, we study the skyrmion spin texture created in a cylindrical exchange-coupled magnetic core-shell nanodisk (Co/CoPt) without DMI. The formation as well as the evolution of the skyrmion spin texture with different applied fields have been investigated to demonstrate the stability and controllability of the skyrmion spin texture in magnetic core-shell nanodisks.

Fig. 1a shows the cylindrical exchange-coupled magnetic core (Co)-shell (CoPt) nanodisk studied in this paper, where the radiuses of the core and the whole regions are represented by r and R , respectively. t denotes the thickness of the disk. Here, $R = 75$ nm, $r = 45$ nm, and $t = 8$ nm. Magnetic parameters are adopted from Ref. [9]: $M_S^{\text{Co}} = 1.4 \times 10^6$ A/m, $A^{\text{Co}} = 2.5 \times 10^{-11}$ J/m, and $K^{\text{Co}} = 0$ J/m³; $M_S^{\text{CoPt}} = 0.5 \times 10^6$ A/m, $A^{\text{CoPt}} = 1.5 \times 10^{-11}$ J/m, and $K^{\text{CoPt}} = 4.0 \times 10^5$ J/m³. The interlayer exchange constant $A^{\text{int}} = (A^{\text{Co}} + A^{\text{CoPt}})/2$. The simulations are performed by the object-oriented micromagnetic framework (OOMMF) package implemented by National Institute of Standards and Technology [13], in which the time-dependent magnetization dynamics is governed by the well-known Landau-Lifshitz-Gilbert (LLG) equation with the average energy density including the exchange energy, the anisotropy energy, the applied field (Zeeman) energy, and the

magnetostatic (demagnetization) energy. Gilbert damping coefficient α is set to 0.3. In our case, the magnetocrystalline exchange length $\left(\sqrt{\frac{A}{K}}\right)$ and the magnetostatic exchange length $\left(\sqrt{\frac{2A}{\mu_0 M_S^2}}\right)$ for Co equal ∞ and 4.5 nm, and the magnetocrystalline and the magnetostatic exchange length for CoPt equal 6.1 nm and 9.7 nm. Hence, in order to ensure the numerical accuracy with reasonable computational efficacy, the model is discretized into cells of 2 nm \times 2 nm \times 2 nm in all the simulations.

II. SINGLE SKYRMION IN A CORE-SHELL NANODISK

At zero applied field ($H = 0$ T), a skyrmion spin structure has been formed in the exchange-coupled magnetic core-shell nanodisk without DMI, as shown in Fig. 1b, where m_z in the center equals to -1, and gradually increases to 1 at the outer edge of the shell. The formation of the skyrmion spin texture can be achieved by the relaxation of the initial state, where the core magnetization orients randomly and the shell magnetization in the $+z$ direction. The random distribution of magnetization in the core can be obtained with local heating. [14] The skyrmion spin texture in the core-shell nanodisk is formed due to the exchange coupling between the core and the magnetostatic interaction. The skyrmion spin texture has also been investigated with external magnetic fields H applied along $+z$ axis and $-z$ axis, respectively. The modulus of the applied field is increased from 0 T to 2 T with a step size of 0.01 T. The dependence of the average z -component of the magnetization M_z and skyrmion number S on the applied field H are shown in Fig. 2a and 2b, where the skyrmion number is calculated by $S = -\frac{1}{4\pi} \int \mathbf{m} \cdot \left(\frac{\partial \mathbf{m}}{\partial x} \times \frac{\partial \mathbf{m}}{\partial y}\right) dx dy$ [15] with $\mathbf{m} = \mathbf{M}/M_S$.

Fig. 2 HERE

In Fig. 2a, magnetic field along $+z$ axis have been applied on the core-shell disk with skyrmion spin texture. At $H = 0.85$ T, the magnetization in the core rotates to $+z$ direction with increasing the applied field, while the magnetization of the skyrmion core remains along the $-z$ direction. The magnetization of the skyrmion core is acutely reversed to $+z$ direction at $H = 0.86$ T with a skyrmion number of 0. In Fig. 2b, magnetic field along $-z$ axis have been applied on the core-shell disk with skyrmion spin texture. At $H = -0.47$ T, the skyrmion spin structure remains well with skyrmion number $S = 1$, even if the magnetization has a bit rotation, which can be seen from the snapshot of the magnetization configuration. At $H = -0.48$ T, the magnetization in the shell reverses to $-z$ axis with skyrmion number $S = 0$. During this process the topological charge (*i.e.*, the skyrmion number) of the core-shell nanodisk changes from 1 to 0.

Fig. 2c shows the $m_z (M_z/M_s)$ profiles along the symmetry lines (red dash lines in Fig. 2a and 2b) for the core-shell nanodisk. As the applied field increases from 0 to 2T, the magnetization in the core rotate with increasing applied field leading the increase of m_z , while the magnetization in the center of the nanodisk keep $-z$ direction, which can be seen from the line of $H = 0.85$ T in Fig. 2c. As $H = 0.86$ T, the magnetization in the center rotate to $+z$ orientation, resulting $S = 0$. As the further increase of applied field, the magnetization in the core gradually reach $+z$ direction. As $H = 1.37$ T, the magnetization nanodisk reaches the uniform state in $+z$ direction. As the applied field decreased from 0 to -2 T, the magnetization in the shell rotate when the applied field decreases to -0.48 T, resulting in the sharp drop of M_z in Fig. 2b. As the further decrease of applied field, the magnetization in the core gradually reach $-z$ direction. As H decreases to -1.37 T, the magnetization nanodisk reaches the uniform state in $+z$ direction. It also can be understood that the skyrmion core size of the skyrmion spin texture can be tuned by the external magnetic field which is applied perpendicularly to the disk plane in a certain range, and is also an important feature of the system for realistic applications.

III. CONCLUSION

In summary, the skyrmion spin texture can exist in exchange-coupled magnetic core-shell nanodisks. The annihilation of the skyrmion spin structure has been observed for a large enough applied field. For Co/CoPt core-shell nanodisks with the investigated size, the skyrmion spin structure will be destroyed at $H = -0.48$ T with the same direction of magnetization in the skyrmion core or at $H = 0.86$ T with the opposite direction of magnetization in the skyrmion core. During the process of the skyrmion spin texture annihilation, the magnetization vectors in the shell are easier to be reversed than those of the skyrmion core, although both require the presence of an applied field up to ~ 0.5 T. With the stability and controllability of magnetic states, the exchange-coupled magnetic core-shell nanodisks can make a high potential for future storage media and devices, with the storage of data in the form of skyrmions.

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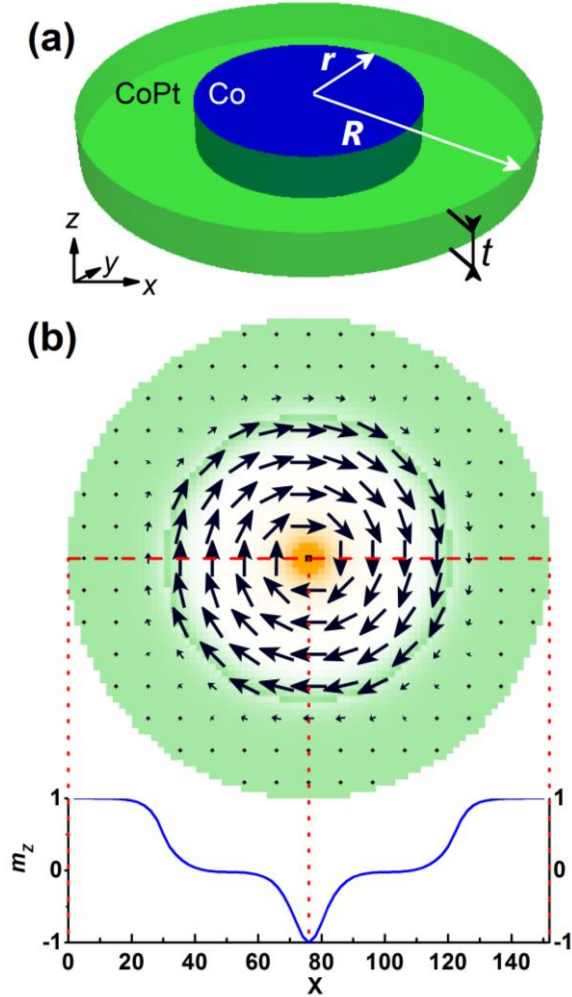


Fig. 1. (a) Core-shell nanodisk with radius r and R . The thickness of the disk is presented by t . (b) The magnetization states and m_z (M_z/M_s) profiles along the symmetry line (red dash line) for the core-shell disk. The arrows denote the in-plane component of the magnetization, while the out-of-plane component of the magnetization is color coded, *i.e.*, green is out of plane, white is in-plane, orange is into the plane.

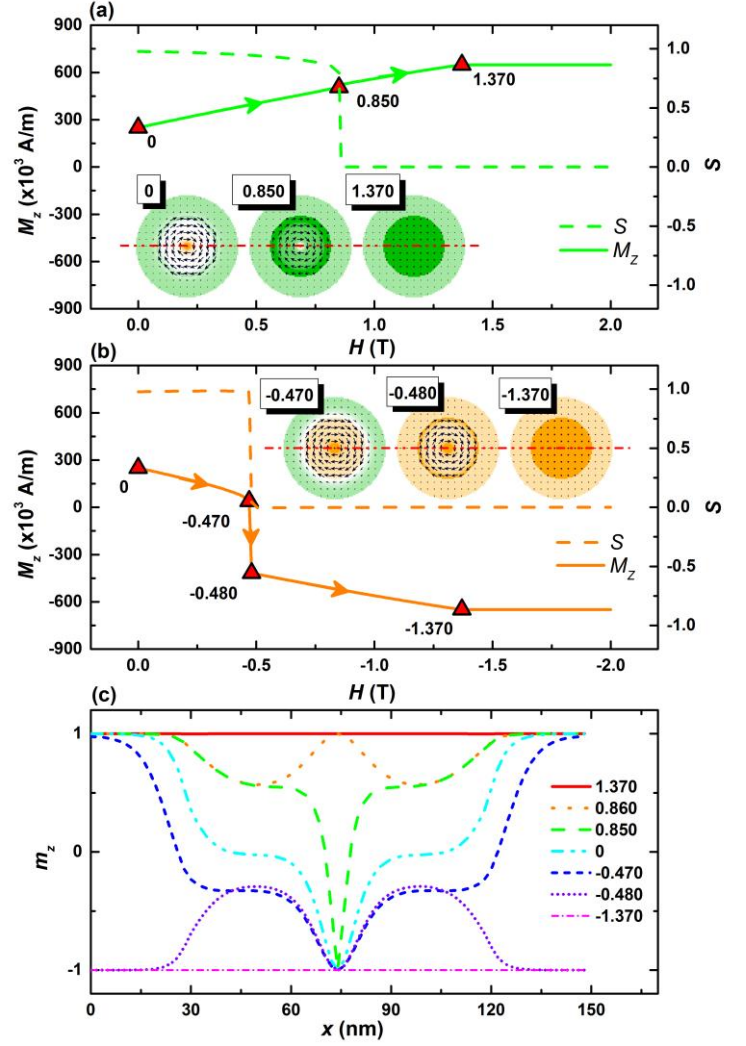


Fig. 2. The average magnetization z -component M_z and skyrmion number S dependence on the applied field H along (a) $+z$ axis and (b) $-z$ axis. The inset in (a) and (b) are the magnetization states at the picked value of H (marked with red triangle). (c) m_z (M_z/M_s) profiles along the symmetry lines (red dash lines in the inset) for the core-shell disk.